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STATE OF THE ART REVIEW

CRYOGENIC COOLING OF INFRARED ELECTRONICS

I. B. Fieldhouse
R. W. Porter

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Infrared detection devices generally require approximately 1 W of cooling at 10 to 100 K. Among the cryocoolers currently available commercially, closed-cycle devices offer advantages over open-cycle types in terms of logistics of storage and maintenance, compactness, and light weight. Reciprocating devices, such as those operating on the Stirling, Vuilleumier, Solvay, and Ericsson cycles, appear generally suitable. Devices incorporating Joule-Thomson (J-T) expansion valves suffer from potential clogging of the active element, the valve. Thermoelectric (Peltier) devices are conceptually attractive, but material limitations have prevented their development for the cooling range of interest. Turbo cryocoolers are potentially attractive because they experience no pressure or force fluctuations, but are perhaps more suitable for larger cooling loads. Each cryocooler application has special needs that can best be met with a custom design that is specified early in the system program in cooperation with the cryocooler and electro-optic designers. A number of U.S. and foreign manufacturers produce closed-cycle cryocoolers suitable for IR detectors. Generally, these devices have a cooling capacity of about (SEE REVERSE - continue)

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SUMMARY

Infrared detection devices generally require on the order of 1 W of cooling at 10 to 100 K, typically 80 K. A number of devices are currently commercially available for providing the necessary cooling. Closed-cycle devices offer advantages over open-cycle devices in terms of the logistics of storage and maintenance and in terms of being compact and lightweight, important factors in missile and high-performance aircraft applications as well as in ground-based combat equipment. Reciprocating devices, such as those operating on the Stirling, Vuilleumier, Solvay, and Ericsson cycles and the like, appear generally suitable.

Devices incorporating Joule-Thomson (J-T) expansion valves suffer from potential clogging of the active element, the valve, due to the contaminants always present. Passive radiators may have suitable applications in space, where a low-temperature cooling reservoir (space itself) is available, but they are generally not suitable for other applications. Thermoelectric (Peltier) devices are conceptually attractive, but material limitations have prevented their development for the cooling range of interest. Turbo cryocoolers are potentially attractive because they experience no pressure or force fluctuations, but are perhaps more suitable for larger cooling loads.

Each cryocooler application has special needs that can best be met with a custom design that is specified early in the system program in cooperation with the cryocooler and electro-optic designers. One interesting approach to system integration is that afforded by microminiaturization. Microminiaturization involves etching the cryocooler conduits, heat exchangers, etc., into a substrate, with specially designed companion diaphragm compressors used for power. At present, only J-T cycles appear to be available. While these are susceptible to clogging, the developers allude to a design concept incorporating redundant circuit paths, thereby achieving the desired reliability, and to extending the concept to other cycles.

Early cryocoolers had to have long life and high reliability, which led to conservative designs incorporating oil-lubricated compressors of large size

and weight. The Gifford-McMahon cryocooler served well in such applications as ground-based satellite stations and the forward-looking infrared (FLIR) detector of the B-52 bomber. However, high-performance aircraft applications require higher operating speeds and pressures in order to reduce size, weight, and input power. Dry lubrication is often used, and shorter life and maintenance intervals are accepted as being necessary to achieve constraints. The Stirling cycle and its variations, such as the Ericsson cycle with a rotating piston and ported cylinder, seem especially useful. The Vuilleumier cycle, which is principally thermally driven, offers the potential of reducing operating and maintenance costs over the entire life cycle because of advantages in reduced wear due to lower pressure operation. In space, magnetic bearings and direct linear drive appear to be necessary in order to achieve the desired long life, which today is typically targeted as five years.

The above considerations suggest that for missile applications the ordinary miniature Stirling cycle, or its related Solvay or Ericsson cycles, may be most suitable. In this application, maintenance required in connection with normal operation is not an issue. Instead, one needs high performance in terms of compactness, lightness, and low power consumption with reliability for one-shot operation. Of course, ground logistics may require testing under active operation, but this would probably entail relatively few hours compared with aircraft or spacecraft applications. The ideal device would be sealed and ready on demand, either for testing or for deployment. If a low degree of microphonics is required, the split Stirling cycle (or related cycle) may be advantageous so that the active cooling element can be separated from the rest of the device, thereby minimizing interference. Nonmagnetic materials may also be used in either an integrated or split system. Through staging, lower temperatures can be achieved, depending on the requirements of the sensor to be cooled.

A number of U.S. and foreign manufacturers produce closed-cycle cryocoolers suitable for IR detectors. Generally, these have a cooling capacity of about 0.25-2.0 W at about 80 K. The devices currently available are predominantly Stirling cycles, including both split and integrated versions, although there are also a number of Joule-Thomson devices and a few Vuilleumier and Gifford-McMahon units. Some of the cryocoolers qualify for characterization as so-called common-module devices meeting military size, weight, and performance requirements.

A large number of organizations are doing sponsored and proprietary research in cryocooler technology. Essentially, research and development can be classified in terms of cycle analysis, loss mechanisms, regenerator development, heat exchanger design, expander design and development, compressor development, seal material, and contamination elimination.

1. INTRODUCTION

1.1 CRYOGENIC COOLING OF INFRARED ELECTRONICS

This report describes the status of the production of cryogenic cooling at temperatures suitable for infrared (IR) detector electronics. IR devices are essentially heat-sensing instruments and must be kept at low temperatures in order to respond to the source of interest. Typically, those devices operating at temperatures of 100 K require a few watts of cooling while those operating near 4 K require only milliwatts.

Military applications of IR detectors date to World War II, with uses for sensing engines and people.[1] Generally, IR detectors sense emissions in the range of 1 to 25 μm. Two types of devices are normally recognized: quantum, including photoconducting and photovoltaic; and thermal, including bolometric, pyroelectric-dipole, and thermocouple. The quantum devices are more sensitive whereas the thermal devices are more linear. Noise is a particular problem, with increasingly greater demands on sensitivity.

Noise in IR systems is due to (1) photon noise, or so-called dark current; (2) detector noise due to thermal agitation; (3) flicker or contact-surface noise; (4) differential temperatures; and (5) vibration, or so-called microphonics.

An important figure-of-merit parameter of an IR device is its detectivity, D, which is the reciprocal of the Noise Equivalent Power, NEP. The NEP is the incident power resulting in a signal-to-noise ratio of unity. Contemporary 256- and 512-element arrays have NEP values of 3-4 x 10^{-17} W when cryogenically cooled from 80 to 25 K and provide resolution to 0.03 K.[2] Quantity D is often corrected theoretically for area, A, and bandwidth, df, as represented by $D^* = D(A \cdot df)^{0.5}$. A reduction in temperature of the IR system increases D*.

Current applications of semiconductors include field effect transistors (FETs) and junction FETs (JFETs) used as IR sensors.[3] In addition to a reduction of background noise, the benefits of cryogenic cooling include increased speed, reduced contact resistance, reduced dielectric losses, greater thermal conductivity of certain semiconductors, reduced so-called thermal voltage allowing lower electrical voltage, and reduced temperature-dependent degradation such as interdiffusion, corrosion, and electromigration. A possible negative effect is induced thermal stress. In addition, other effects may prove limiting irrespective of cooling: scattering due to impurities and defects, statistical variation, cross-talk (particularly as spacing decreases), and quantum effects.

Numerous methods exist for cryogenic cooling and the production of suitable low temperatures. Open-cycle devices employ a stored substance that is used once and then discharged, a process increasingly viewed as impractical in terms of capacity and weight. Mechanical closed-cycle devices suffer from vibration, interference, temperature ripple, and a lack of reliability. Further, their efficiency decreases with temperature, compounding their problems, especially below 20 K. While certain thermal and thermoelectric devices have been developed, they too have limitations preventing their general application. In the last two decades, an enormous research effort has been directed toward advancing the technology of cryogenic cooling suitable for electronic applications. Depending on the cooling load at the temperature desired, each device has certain advantages and disadvantages. This report attempts to identify the limitations of the candidate devices and to delineate the present status of developments.

While emphasis is given here to the devices producing cooling at low temperatures, certain problems such as interfacing the devices are also considered. Primarily, focus is on indirect-contact heat exchange wherein the cryofluid is separated from the element. However, spray cooling has been used in some applications.[4] Vapor may also be used to reduce thermal stress during initial cooldown. Often, scattering in the optics is due to condensables at 20 to 77 K, due to exhaust plumes, outgassing, etc. In such cases, the optics should be the last element to be cooled in start-up.[5]

A survey of IR detectors for 1975-1984 and a projection for 1985-1994 points out that the Strategic Defense Initiative (SDI) will lead the development of the technology.[6] Many space applications require 15 to 80 K, while in the extreme the Infrared Astronomy Satellite requires 2.8 K. Indeed, stars may be used to calibrate IR sensors.[7] IR spectrometers may be used for atmospheric studies.[8] The stratosphere has a background radiation at 220 K.[9]

In conventional warfare, there is a particular need for defense against sea-skimming missiles and anti-tank weapons. About 50 percent of quantum devices used for IR detection are cryocooled.[10] These include the IR detectors used in numerous tactical missiles such as the Sidewinder AIM-9B and 9D. That cryocooling is potentially critical in such applications is reflected in reliability studies of the F/FB-111 wherein 64 percent of the failures of the IR Tail Warning System were attributed to cryocooler failures.[11]

This report is particularly concerned with applications of this type, especially for tactical missiles. However, the rapid advances in many other applications may prove illuminating and have interchangeable concepts. Thus, the entire spectrum of cryogenic cooling of electronics will receive attention.

1.2 CLASSIFICATION OF DEVICES

In this section cryogenic cooling devices are classified according to their physical construction and mode of operation. The principles of operation and typical applications are described briefly. Various devices of particular interest are reviewed in more detail in Section 2.

1.2.1 Open and Closed Cycles

Open-cycle devices typically employ a working substance that is used once and then discharged. Examples include stored liquids and solids that are evaporated, providing cooling according to their latent heat. In addition, vapor as provided by evaporating liquid or by compressed gas storage may be expanded through a Joule-Thomson valve.[12] A gas is reduced in temperature on expansion through such an adiabatic valve if it is initially at a sufficiently low temperature, i.e., below its inversion temperature. The major problem with this approach is clogging of the valve due to freezing of impurities, which typically condense at higher temperatures than the base fluid. Nevertheless, a device developed for the Army Night Vision Laboratory measures only 3 in. in length and weighs only 2 oz while producing 200 mW of cooling at 77 K for 2 h from 3000 psi storage.[13] Table 1 illustrates the limit of temperatures encountered in open-cycle devices. A series of devices can be used to achieve successively lower temperatures as required.

TABLE 1. CHARACTERISTIC TEMPERATURES OF TYPICAL CRYOFLUIDS AT ATMOSPHERIC PRESSURE[14]

Cryofluid	Temperature of Evaporation, K	Temperature of Inversion,[a] K
Oxygen	90	890
Argon	87	720
Nitrogen	77	620
Neon	27	225
Hydrogen	20	205
Helium	4	50

[a]For Joule-Thomson effect.

Interestingly, Hudson[14] classifies the passive radiative cooler as an open-cycle device. Here, heat is radiated to a remote heat sink such as outer space. Radiative coolers generally have elements such as heat pipes in order to conduct heat from the cold plate to be cooled. However, these devices are often limited to temperatures near 100 K. Further, their use in terrestrial applications is probably impractical due to the general lack of an adequate low-temperature sink and the size of the radiator that would be required in even ideal situations.

More conventional open-cycle liquid systems employ Dewars, which are chambers surrounded by one or more vacuum spaces with radiation shields between them.[15] Pour-type and transfer-type units are commonly used in the laboratory for testing IR devices. Liquid and solid storage devices have also been used routinely in space. For example, one application entails 800 mW of cooling at 10 to 125 K, while another has 100 mW at 1.5 to 5.2 K.[16] Typically, liquid helium and solid hydrogen are used.[17]

Devices employing compressed gas and Joule-Thomson expansion can be converted to closed-cycle by recycling the expanded fluid through a compressor. These and numerous other closed-cycle devices are capable of running continuously without expending fluid. Alternatively, they may be started and run on demand. In addition to conventional mechanical cycles, it is possible to incorporate thermal, thermoelectric, and magnetic processes avoiding wear and other problems, but their use is generally limited by practical considerations. Closed-cycle devices are generally more compact and light in weight due to the elimination of the storage reservoir. Recent developments have led to their miniaturization and even microminiaturization.

1.2.2 Mechanical, Thermal, and Electromagnetic Devices

As discussed previously, the Joule-Thomson (J-T) process can be incorporated into a closed cycle (Figure 1) by using a compressor, as well as by adding a recuperator.[12] On a large scale, the system is known as the Linde-Hampson process, which is used for the liquefaction of gases.[18] Addition of the compressor does lead to intensification of the clogging problem due to condensable contaminants from the compressor. As discussed in Section 2, specially designed compressors have been developed in order to reduce this problem. Alternatively, the J-T valve may be replaced with other components less likely to clog. One such component is an expander, or work-producing device; another is a displacer that simply provides expansion without producing work, which is generally not recovered anyway. The Claude cycle (Figure 2) involves both the J-T valve and an expander, and is generally used for commercial liquefaction processes.

The above devices are classified as mechanical because they involve mechanical compressors and/or expanders. Many more variations of these devices exist, which are discussed later in this section and in more detail in Section 2.

Nonmechanical alternatives also exist. For example, the compressor of the J-T process (Figure 1) can be replaced with a so-called thermal compressor[16] using absorption of a metal hydride. Adding heat to a $LaNi_5$ hydride chamber, for example, raises H_2 static pressure from 4 atm at 313 K to 60 atm at 393 K. Removing heat reverses the process.[19] Thus, this is a thermal compressor, which together with a J-T valve and recuperator results in a thermal cycle without moving parts. This system is regarded as an emerging technology of great interest.

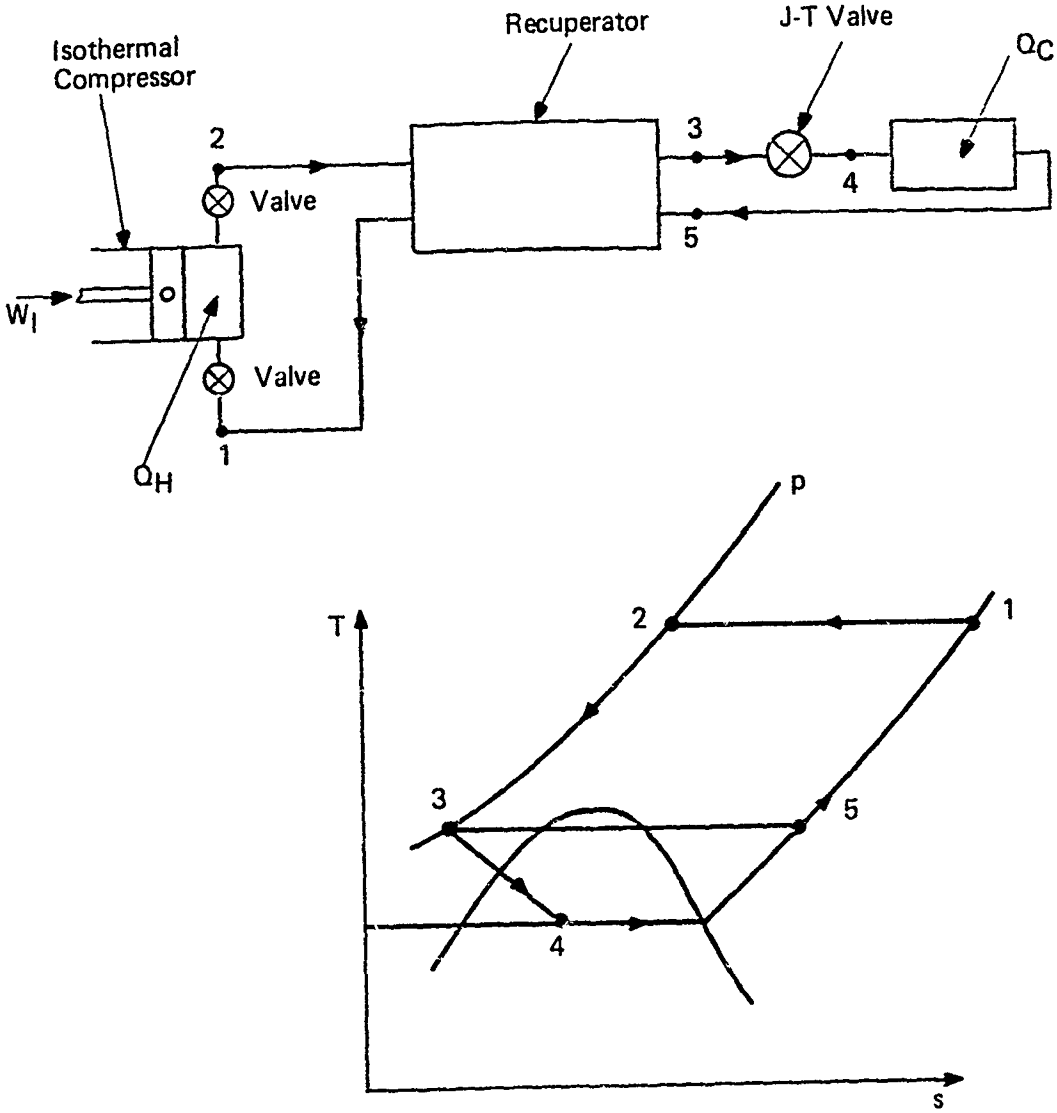

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Figure 1. Joule-Thomson (Linde-Hampson) cycle.

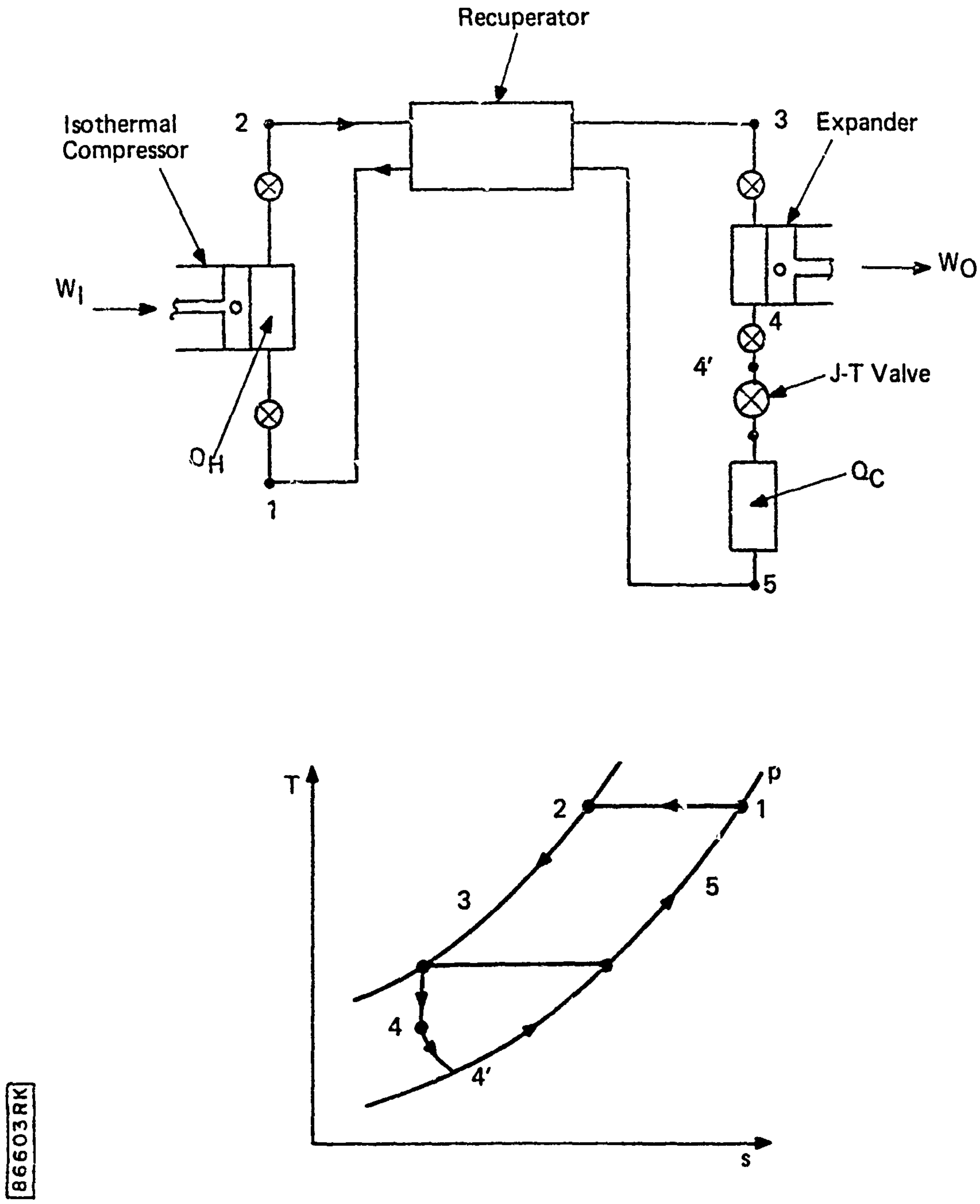

Figure 2. Claude cycle.

Another example of a nonmechanical system is the thermoelectric Peltier cooler. This familiar device for cooling at ordinary temperatures absorbs heat while passing current through an N-P junction and rejects heat while passing the same current through the opposite junction. Unfortunately, only with great difficulty can temperatures at the cold junction be reduced below about 150 K.[12] However, optimal design, cascading, and good insulation can be combined to maximize performance in a convenient package.

The Ettinghausen effect, involving a crossed electrical current and magnetic field, can also be used to achieve a temperature gradient. For example, a bismuth-antimony crystal subjected to 11 and 15 kG produced a temperature difference of 36 K at 156 K.[12] However, these devices have found little application probably because of the electromagnetic requirement, which is often incompatible with the environment of the device to be cooled.

Finally, demagnetization of paramagnetic salts produces very low temperature.[18] Unfortunately, these devices are best suited to very small cooling loads encountered on the approach to absolute-zero temperature. Nevertheless, work is proceeding at NASA and Los Alamos on these devices.[16] A critical anomaly is the very large magnetic fields used in the initial magnetization process. Such fields would likely be produced by cryomagnets, themselves requiring cryogenic cooling. Thus, a cascade or bootstrap approach is required, complicating the logistics of operation. Further, the very high magnetic fields required may not be compatible with many applications.

Of the above electromagnetic devices, only the thermoelectric appear at all practical at present, and these are discussed further in Section 2.

For further subclassification of mechanical devices, they can be conveniently identified as illustrated in Table 2 in terms of:

(1) Type of heat exchanger
(2) Type of expansion device
(3) Reciprocating or turbo type machinery
(4) Valves or no valves.

TABLE 2. MECHANICAL REFRIGERATION CYCLES

Type of Heat Exchanger and Use of Compressor Valves	Reciprocating Expansion Device (Reciprocating Compressor)			
	None	Expander (Work Out)	Displacer (No Work)	Turbo-machinery
Recuperator (quasi-steady)				
Valves	Linde (J-T)	Claude (J-T)	--	--
No Valves	--	--	--	Brayton/ Ericsson
Regenerator (storage)				
Valves	--	Solvay	Gifford-McMahon	--
No valves	--	--	Stirling/ Vuilleumier	--

1.2.3 Type of Heat Exchanger

The Linde-Hampson and Claude systems have already been discussed. Generally, both of these involve valves when used with conventional-type reciprocating compressors. They also have recuperators in order to precool flow ahead of the J-T valve (Linde-Hampson) or ahead of the expander (Claude). It is also possible to use a heat storage device or regenerator instead of a recuperator, resulting in the so-called Solvay cycle.[12]

As discussed below, several other important cycles also use recuperators and find many applications.

1.2.4 Expander and Displacer Devices

Rather than produce work in an expander of the Solvay cycle, the Gifford-McMahon (G-M) cycle has a so-called displacer. The displacer is phased with the compressor in order to provide expansion without producing work, which is generally not recovered anyway. The G-M cycle is widely used in ground-based satellite transmission receiving stations.[20] Unfortunately, these devices are too heavy and bulky for many applications.

Considerable effort has been expended in developing the Stirling cycle,[12] which operates without valves while using a regenerator together with a compressor and expander (see Figure 3). Figure 3 represents the conceptual cycle and not the practical device that has evolved. The Stirling cycle is essentially a constant volume device due to the phasing of the compressor and expander. Heat is alternately charged and discharged in the recuperator. The Stirling cycle has been widely studied and highly developed in miniature form for military and commercial applications.[21-28] Special efforts have been made to extend life and achieve a compact, efficient design.

The Stirling cycle ideally has the same efficiency as the Carnot cycle, the maximum theoretically possible, because heat is added and rejected at the extreme temperatures encountered. Thus, the Stirling cycle is potentially one of the most efficient, compact, and low-power designs possible.

The above devices operate with mechanical compressors. Alternatively, the Vuilleumier (VM) cycle uses heat addition to supplement the compression of a reciprocating device.[29] In this way the high stress of a conventional compressor can be drastically reduced, thereby extending life. In practice, work is still done on the so-called hot displacer in order to control phasing with the expander and overcome friction. An idealized version of the cycle is shown in Figure 4.[30] The VM cycle is sometimes classified as a Stirling heat engine driving a Stirling refrigerator (see Table 2).

1.2.5 Reciprocating and Turbo Machinery

The above devices all incorporate reciprocating compressors, displacers, and/or expanders. However, it is also possible to apply the Brayton cycle in reverse with rotating machinery,[24] as shown in Figure 5. These devices are potentially very attractive because they operate in the steady-flow, steady-state mode. In practice, they are limited because of the extreme speeds required in order to achieve desired performance.

Devices have also been developed involving rotary compressors, which are thermodynamically similar to reciprocating devices but which have better dynamical characteristics.[31] There are also devices with pistons that reciprocate in the usual manner but also rotate, exposing and closing ports in such a way as to eliminate the valves that would otherwise be required. Thus, either the Stirling cycle may be used or the Ericsson cycle in similar hardware.

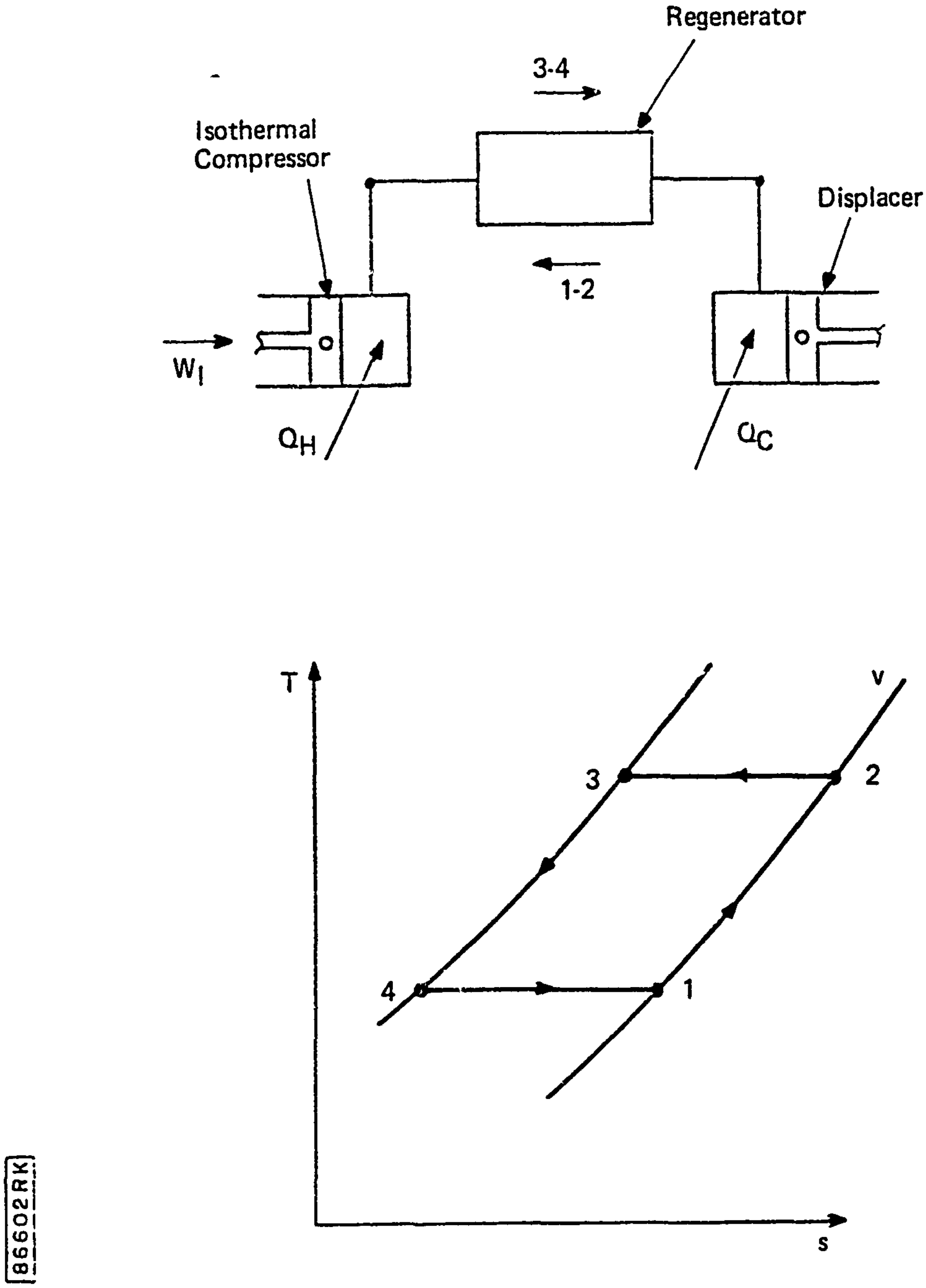

Figure 3. Ideal Stirling cycle.

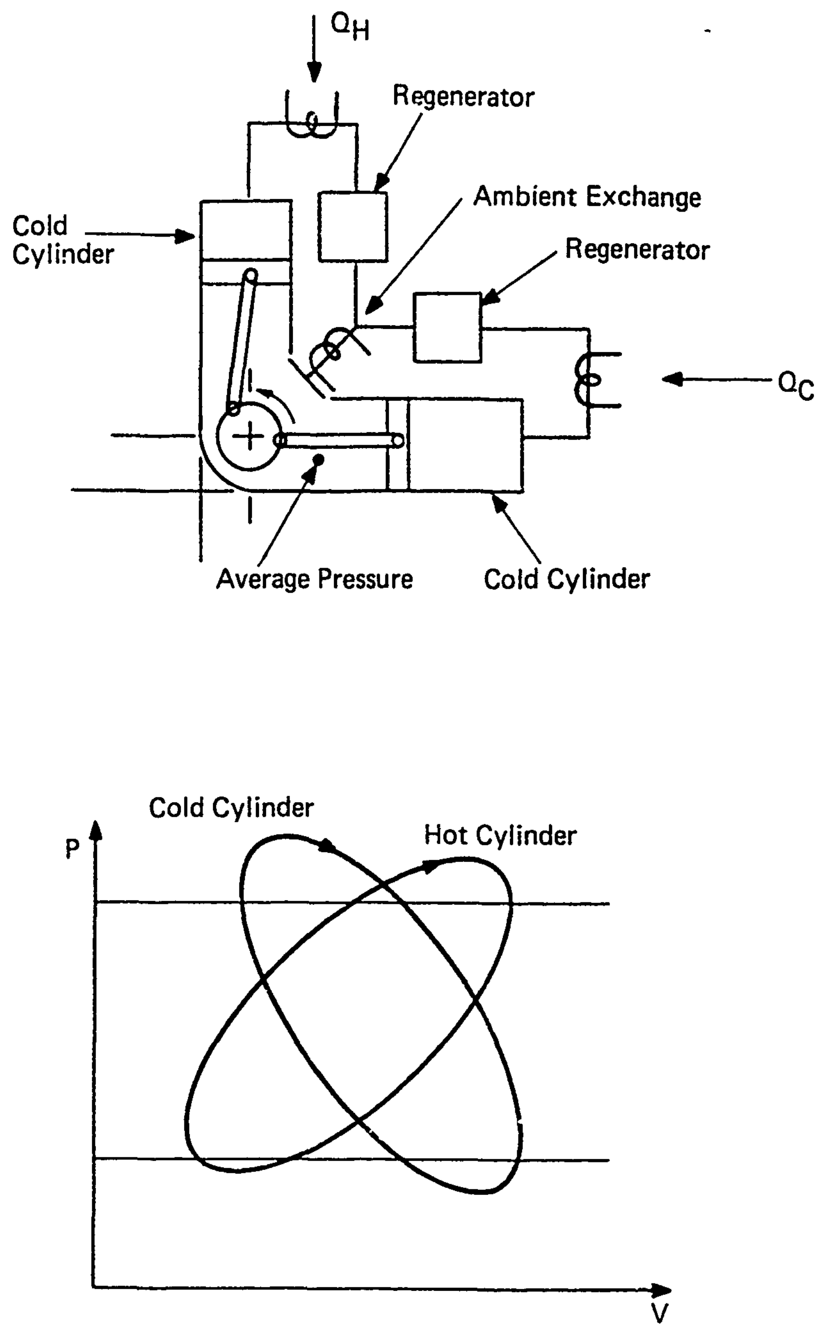

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Figure 4. Vuilleumier cycle.

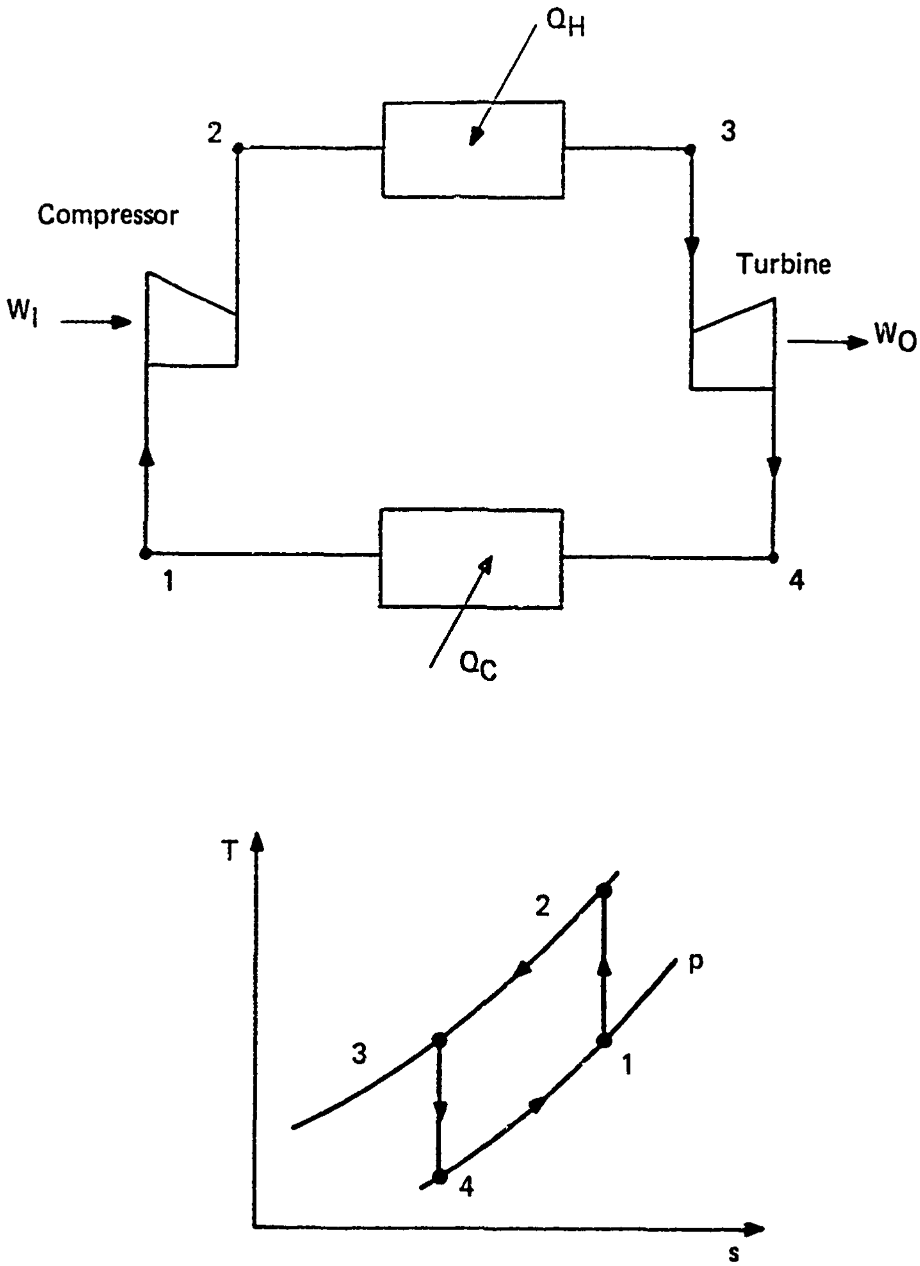

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Figure 5. Reversed Brayton cycle.

1.2.6 Valves or No Valves

As indicated above and in Table 2, the Linde (J-T), Claude, Solvay, and Gifford-McMahon cycles operate with valves, whereas the Brayton, Ericsson, Stirling, and Vuilleumier cycles operate without valves.

2. REVIEW OF CANDIDATE SYSTEMS

2.1 OPEN-CYCLE DEVICES

The systems reviewed here are cryocooling devices that expend substances in their normal operation--namely, liquids and solids undergoing phase change and Joule-Thomson (J-T) expansion processes.

2.1.1 Liquid Systems

Two types of liquid systems rely on the latent heat capacity of a cryogenic fluid selected according to the temperature desired (Table 1): the pour-fill Dewar and the transfer device.

The pour-fill Dewar is essentially a flask with vacuum-jacketed walls, radiation shielding, and conventional insulation--little changed since its invention by James Dewar in 1392.[15] Samples may be readily cooled in the laboratory by mounting them on the outside of the inner wall. The Dewar is generally precooled with liquid nitrogen if cooling below 77 K is required, after which liquid helium is added from the storage Dewar. Liquid helium is available commercially in many areas or may be produced on site by liquefaction machines operating on thermodynamic cycles similar to the Gifford-McMahon cycle. Temperatures above 4 K are generally maintained by incorporating electrical heating elements. Lower temperatures can be achieved by using reduced pressures.[12]

Prior to the mid-1960s, Dewars were widely used in military applications because better alternatives were lacking. However, the size of the required storage Dewars, limitations on the orientation, the burn hazards of handling cryofluids by field personnel, and the combustion hazard of hydrogen and oxygen (where employed) motivated the development of other alternatives not requiring handling or even storage of cryofluids.

Nevertheless, Dewars appear to have certain applications in space for the range of 1.6 to 4.2 K using normal and superfluid helium.[16] Thus, the Infrared Astronomical Satellite (IRAS) incorporates 1.8 K superfluid helium in a 540-L toroidal 5083 aluminum alloy tank, the inner ring of which receives the telescope mounting ring. Thermal protection is provided by three vapor-cooled shields and multilayer insulation. Radiant cooling reduces heat leaks. The Dewar, manufactured by Ball Aerospace Systems Division, recently flew successfully with orbital data indicating a lifetime of 10 to 11 months.[17] A similar device is intended for the Cosmic Background Explorer (COBE) mission operating at 1.6 K. Numerous other NASA missions are planned calling for ultra-low temperature cooling by means of liquid Dewars.

Many of the limitations of pour-fill Dewars, particularly in laboratory applications, can be overcome with the transfer device. In this system, flow of the cryogenic fluid is regulated from a storage Dewar, often with automatic temperature control of 0.01 K from 2 to 20 K, 0.1 K from 20 to 77 K, and 0.3 K from 77 to 300 K, and with arbitrary orientation. In the Heli-Tran device, manufactured by Advanced Products of Air Products, Inc., cooldown from ambient conditions to 4.2 K and no load can be accommodated in less than 20 min and held with a refrigeration capacity of several hundred milliwatts using approximately 0.75 L/h of liquid helium. These devices are well suited for laboratory test stations for IR devices.[15]

Transfer devices can also be used in airborne applications.[14] The transfer line to the remotely located sensor need not be insulated because of the Leidenfrost pheonomenon, wherein a layer of vapor phase lines the transfer line wall and wherein the liquid droplets are carried by a moving gas stream. There is apparently an optimum diameter of the transfer tube, about 0.05 to 0.10 in. for liquid nitrogen, in order to maintain the effect. Aircraft applications require that the pressure of the storage Dewar be regulated with altitude by means of heaters and possibly intake vents. The transfer line is relatively small and flexible, and can be attached to a cold plate mounted on a moving structure for guidance purposes. Although the logistics of employing transfer devices are better than pour-fill Dewars and many air bases have facilities for servicing other similar flight systems, the major disadvantage of the transfer device is the need for periodic refilling. Both the Army[13] and the Navy[26] recognize this disadvantage and have sponsored extensive programs oriented toward the development of closed-cycle devices.

2.1.2 Solid Systems

Solid cryogens utilize the heat of sublimation to absorb the cooling load at constant temperature as regulated by the pressure that is maintained consistent with venting the effluents, typically 0.1 torr.[16] Solids have been extensively used in space applications, with exploitation of their increased energy density and lack of sloshing compared with liquids. Solids also are sometimes favored over mechanical devices because they are vibration-free and require no inherent input power. A two-stage methane/ammonia solid cooler manufactured by Ball Aerospace Systems Division flew on the High Energy Astronomical Observatory (HEAO). Approximately 200 to 400 mW at 80 K are provided by a 75-kg package of 56-cm diameter and 81-cm length and 8 to 11 month lifetime. Unfortunately, solid systems increase rapidly in weight and volume with capacity, have relatively high cost, and, like liquid systems, suffer from inconvenient ground logistics. While solid cooling is expected to serve a need in future space missions for satellites and the Space Shuttle, flights of sufficiently long duration and/or higher cooling loads will ultimately require closed-cycle cooling.

2.1.3 Joule-Thomson Systems

Work at Jet Propulsion Laboratory indicates that Joule-Thomson expansions can be cascaded using various fluids (see Table 1) with temperatures from 300 to 4.2 K in four stages.[32] A storage reservoir or remote compressor involves no bulky or moving parts near the device which need cooling. A typical design provides 1.2 W at 165 K, 1 W at 84 K, and 25 mW at 5 K. Xie[33] describes a novel two-phase-flow valve with integral fin-tube heat exchanger developed at the Shanghai Institute of Physics. Using 4 L/min of liquid nitrogen, 4 W of refrigeration are provided at 20 K with cooldown at no load from ambient in 0.5 to 1 min. Air Products and Chemicals[34] describes a 8.5 lbm device targeted to provide 200 mW of refrigeration at an unspecified temperature for application to a U.S. Army night vision device. The storage tank is the largest and heaviest component, a disadvantage shared by other open-cycle devices. However, tests indicate very efficient operation, with 96 percent recovery of the 212 mWh available in the 173 in^3 tank at 3800 psia. In devices of this type, flow should be regulated according to cooling demand in order to conserve cryofluid.

Perhaps the most serious problem with J-T systems is the clogging of the expansion valve with condensed contaminants. For this reason, the cryofluid must be of high purity and the system purged before use. Even so, the valve may require periodic heating in order to free it.

One of the most exciting advances in cryogenic cooling involves the microminiaturization of the Joule-Thomson process on substrates by photolithography similar to the process used to produce microminiature electronics.[35] Gas passages as narrow as 50 μm and as shallow as 5 μm are etched in glass plates, which are then laminated together. For example, 1.5 L/min of nitrogen at 1800 psia can provide 250 mW of refrigeration at 80 K after 8 to 12 min of cooldown. Indeed, cooldown in as little as 4 s can be achieved using 3800 psia and a disk geometry. Possible applications include IR tactical missiles employing onboard gas-bottle reservoirs.

In a comprehensive article, Little[36] has reviewed the theory and status of microminiature cooling, pointing out the potential to achieve about 100 mW of cooling at 20 K and 4 K using hydrogen and helium stages. The motivation of microminiaturization is associated with the scaling laws of going to the small loads of ultra-low temperatures. One simply must scale down to where the use of substrates appears to be the only course of action. Coincidentally, the flow circuits can be mass-produced on large boards and separated as required. The microminiature size of the cooling device may be well suited to the device requiring cooling, allowing a degree of system integration not otherwise feasible. The small size is also compatible with reduced gas consumption. Currently, a J-T device is used in the 500 x 500 CCD silicon optical detector array of the Lick Observatory, but it requires warming every 40 h to clear the valve. Redundant paths may overcome this critical problem.

2.2 CLOSED-CYCLE DEVICES

2.2.1 Joule-Thomson Systems

The Linde-Hampson cycle incorporating a gas compressor, J-T valve, and recuperator (Figure 1) is theoretically suitable for cooling IR devices, although it is primarily used on a large scale for cryofluid liquefaction.[18] At the other end of the spectrum, miniature diaphragm compressors are under development for use with the microminiature J-T system discussed earlier.[36]

Commercial development was expected in two years, i.e., 1986. Another option mentioned is the incorporation of the gas-absorption compressor employing a metal hydride such as $LaNi_5$ with no moving parts. Such a device could have virtually an infinite life.

The metal-hydride gas-absorption or thermal compressor was developed at Jet Propulsion Laboratory for NASA.[37] In essence, adding heat increases the static pressure in the device, substituting for mechanical compression. Similarly, removing heat reverses the process.

Jones and Golben[19] discuss the present status of absorption compression, currently applied to the J-T process but envisioned for possible use in other cycles as well. The heat source for the device can be low-grade, making its use attractive for space using solar heating or radioactive decay. Present experimental devices involving the J-T valve still suffer from clogging, although the use of high-grade cryofluid, clean-room assembly, and filtering are expected to control the problem. A 500-h running time has been achieved with operation below 30 K. A particular problem with the metal-hydride system is the instability of the hydride element, which mechanically breaks down on thermal cycling. However, this characteristic appears to have been accommodated in the current design philosophy.

The use of microminiaturization and metal-hydride thermal compression are potentially far-reaching advances in closed-cycle cryocooling that transcend their present applications in Joule-Thomson processes. Devices could be standardized for various applications just as integrated circuits are standardized for various logical applications. One can even imagine micro-cryocoolers fully integrated into microelectronic elements at the time of manufacture, operating on de[illegible] and providing the necessary cooling just as other parts of the device p[illegible] their own particular functions. In tactical missile and similar applications, the heat input to the thermal compressor could be provided electrically. Thus, the dormant sensor would be entirely self-contained, sealed, and ready to operate in seconds on demand.

As discussed in Section 1 and noted in Table 2, the Claude cycle can be considered a modification of the Linde-Hampson or Joule-Thomson cycle through the addition of a work-producing expander. Typical arrangements of the cycle in terms of the relative positions of the two active cooling components are given by Hsieh[18] and by Louie and Radebaugh.[38] The addition of the expander in the Claude cycle evidently reduces reliability, because the expander is the component undergoing failure most frequently and requiring the most maintenance. The Claude cycle appears to be used primarily in large sizes for commercial liquefaction processes.

2.2.2 Gifford-McMahon Cycle

As noted previously, a J-T valve is subject to clogging due to the condensation of impurities, especially from the compressor. Thus, it may be desirable to eliminate the J-T valve from the Linde-Hampson (J-T) process and use an alternative component for cold production. One such device is an expander, which produces a drop in temperature together with the output of work. When the recuperator (which exchanges heat between the streams to and from the cold element) is replaced by a regenerator (which stores and releases heat from the same stream intermittently flowing to the cold element now mounted on the expander), the resulting device is known as the Solvay cycle. Finally, the expander can be replaced with a cold-side displacer integrated with the regenerator. In this case the displacer does not produce work, but rather only the desired cold production, leading to the so-called Gifford-McMahon cycle. Because of the similarities in the above devices and because of the wider application, the Gifford-McMahon cycle is discussed here as a representative device.

Unfortunately, G-M devices appear to be bulky and ill-suited to portable and airborne applications, where weight is a premium parameter. For example, a G-M cryocooler available from Cryogenic Technology, Inc. (CTI), weighs 96 kg although it provides 15 kW of cooling at 70 K.[19] Further, the device requires periodic maintenance every 2000 to 5000 h due to the need to service its elaborate compressor-oil cleaning system. However, the unit is among the most reliable of those available today, with a mean time between failures (MTBF) of 20,000 h. Essentially, long life is achieved because of a relatively low cycle rate, i.e., about 70 rpm, and because the piston seals are subject to relatively low pressure difference. Unfortunately, the presence of lubricating oil in the system ultimately leads to contamination of the cryofluid.

New applications of the G-M cycle may be possible with a system developed by Leybold-Heraeus GmbH, Federal Republic of Germany.[39] The subject device operates on so-called split cycle wherein the cold displacer is separated appreciably from the compressor, which is the heaviest and bulkiest item in the system. For example, a particular device weighing 6.6 kg exclusive of the compressor was designed for a separation distance of 5 m, with 10 W of cooling at 80 K in the first stage and 2 W of cooling at 20 K in the second stage, in the presence of a 4 tesla magnetic field, which evidently would otherwise preclude use of the device. Cooling to 4.2 K can be achieved by adding a J-T stage. Although other cycles, namely the valveless Stirling and Vuilleumier cycles (discussed below), can also use the split design, their efficiencies are sensitive to the length of the connecting line and its so-called dead volume. Thus, the G-M cycle may enjoy an advantage where a large separation distance is required in a split-cycle design.

2.2.3 Stirling Cycle

The Stirling cycle has a long history as a thermodynamic power cycle of practical interest. However, in terms of modern cryocooling, it can be considered an extension of the Gifford-McMahon cycle achieved by the elimination of valving and by proper phasing of the compressor and displacer (see Table 2 and Figure 3).

The ideal Stirling cycle is conceptually simple: the reversible compressor compresses its contents isothermally, giving off some of the heat of compression in the process, with the displacer fixed. The compressor and displacer then move together in such a way that the charge passes through the regenerator, giving off heat of compression, and into the isothermal displacer volume. The compressor is then stationary, and the displacer continues to expand its charge, producing the refrigeration effect. The process continues with the compressor and displacer moving together in such a way that the charge moves out of the displacer through the regenerator, picking up the heat of compression previously stored, and back into the compressor, thus completing the cycle. The coefficient of performance of the ideal device is the same as that of a Carnot refrigerator for the same hot and cold temperatures of the isothermal compressor and displacer. As discussed by Louie and Radebaugh,[38] the high potential efficiency of this Carnot-limited device, together with its mechanical simplicity, make the Stirling cryocooler one of the most compact, efficient, and reliable of the devices yet commercialized.

A wide variety of Stirling cryocoolers have evolved since the mid-1960s. For example, the compressor and displacer can be integrated into one compact unit or they can be separated by (flexible) tubing, thereby permitting the cooling to occur remotely in conjunction with the smaller displacer mounted on a moving base, and/or in the presence of a high magnetic field, etc. The separate displacer may be driven pneumatically by the compressor or it may be controlled independently. The regenerator may be integrated with the displacer piston or may even be discarded, with the piston and cylinder themselves acting as a so-called gap regenerator. Considerable effort has been expended in improving the components of the Stirling cryocooler, especially in terms of minimizing the wear of the compressor and displacer which leads to contamination and, in terms of improving the regenerator, which is generally recognized as the limiting factor from a thermodynamic point of view. Many of these issues are generic to cryocoolers and are discussed in Section 2.3. At this point, the discussion deals with the Stirling device first as a <u>integrated</u> system and then as a <u>split</u> cycle. In addition, each class will be discussed first in terms of conventional <u>mechanical</u> drives as typically represented by a rotating electrical motor connected to a crank-shaft, and then in terms of direct <u>linear</u> drives wherein the motions of the pistons are induced by electrical solenoids, thereby reducing an element of wear due to side forces of rotating machinery. However, both integrated and split cycles as well as both rotating mechanical and linear electrical drives are currently evolving in parallel as four classes of devices, the choice depending on the application.

One of the early contemporary <u>integrated mechanical</u> Stirling cryocoolers was developed by Malakar Laboratories.[40] The device was delivered to the Air Force (WPAFB) and reached a cold temperature (presumably at no cooling load) of 77 K after 13 min and 37 K after 37 min using 310 W of input power and 100 psig helium as a working fluid. By increasing the helium pressure to 150 psig, performance was increased, leading to a temperature of 77 K after 9 min and 35 K after 29 min using 340 W of input power. The amounts of cooling capable of being sustained by the device at operating temperatures were not reported, nor were data on the size and weight.

Chellis[41] discusses a device produced by Cryogenic Technology Inc. (CTI), also developed for the Air Force (AFFDL), for use in missiles. The device achieved 1 W of cooling at 80 K while operating at 23°C ambient temperature. The device, easily handheld, weighed 3.25 lb and operated with a drive motor using 200 VAC and 400 Hz. Input power was not reported. A life of 250 h was attained. The Stirling device generally was more efficient than competing cycles and had a faster cooldown than the Vuilleumier cycle, although it has less reliability than the Gifford-McMahon cycle.

Pirtle[42,43] discusses a CTI four-stage Stirling cryocooler having a stepped displacer to achieve staged cooling. The objective was to produce 50 mW of cooling at 10 K after 24 h of cooldown while operating with 250 W of input power and while generating little electromagnetic interference and vibration near the cold-side displacer. The device, developed for the Navy (ONR), was intended to be used with superconductive and other low-temperature electronics. The displacer incorporates a gap regenerator in conjunction with a so-called MACOR ceramic cylinder. A die-post displacer guide was intended to reduce side contact, and clearance seals were employed on both the displacer and the standard compressor, which was driven by a shielded DC motor. Unfortunately, an error in the design of the gap regenerator led to achievement of only 95 K rather than 10 K. In addition, problems were identified with the sealing of the ceramic cylinder, leading to a need to remelt the surface in order to seal it from helium penetration and subsequent leaking of the working fluid.

Philips Laboratories, as represented in the U.S. by their subsidiary and by Magnavox, has developed a series of <u>integrated linear-drive</u> Stirling cryocoolers using resonance-free displacers.[44] The Philips model MC-80 was introduced in 1975 producing 1 W at 80 K. This was followed by the model MMC-80 (Magnavox model UA-7011) in 1976, which was a militarized version but not intended for the U.S. standard application to forward looking infrared (FLIR) detection. The unit had a design life of 2500 h MTBF. More recently,[45,46] Philips has developed a cryocooler for NASA intended for satellite applications. This device achieved 5 W of cooling at 65 K after 20 min of cooldown. Intended to have a 3 to 5 year life, tests indicate at least a 2500 h MTBF. The device weighs 20 kg and occupies a volume of 54 L exclusive of electronics. Component tests were intended to resolve a choice between magnetic and air-suspension bearings and to prove the regenerator, displacer, and motor.

Philips has also designed a cryocooler for the Navy (ONR) with three stages to achieve 50 mW of cooling at 10 K using 100 W of input power, or 200 mW of cooling at 10 K using 250 W of input power.[47,48] The 61.5-kg device employs vibration and electromagnetic dampers to provide a low-level operating signature. The displacer is driven resonantly by the compressor or so-called piston motor, driven in turn by a linear moving-coil motor that minimizes side loads. An optical transducer monitors and controls piston motion. The piston seal and bearings are reinforced Teflon, and the piston assembly is made from titanium. The regenerator is of an annular configuration. Axial imbalance is damped by a countermass supported only by springs. The thermal efficiency was limited by the regenerator and loss of specific heat at low temperature. Vibration, electromagnetic, and weight specifications were not met in steady operation, but it was indicated that an intermittent mode might be more favorable.

Berry[49] describes several <u>split mechanical-drive</u> Stirling cycles developed by Hughes for the Air Force (AFFDL) with the objective of low cost, low weight, and small size. One device produced 0.5 W of cooling at 77 K using 80 W of input power. The compressor measures approximately 3 in. in diameter and 4 in. in length, and is separated by 10 in. of tubing from the displacer, which measures about 0.4 in. in diameter and 1.4 in. in length. A second device, with a compressor of approximately twice the size, produced 2 W of cooling at 77 K using 150 W of power, and accommodated a separation distance of 5 ft. The largest device, with a compressor approximately 1 ft in diameter and 1 ft in length and separated 8 ft from a displacer of approximately 2 in. diameter and 2 in. length, produced 2.5 W of cooling at 77 K or 1 W at 25 K. The cost of each of these devices was estimated to be about $1000, achievable because of low costs of design and manufacture with a modular design, shared parts, etc. Later,[50] Hughes fabricated ten of the 0.5 W devices as part of a development program for the AIM-9L missile. The devices weighed approximately 7 lb, and they had a cooldown of 3 min from ambient conditions. The units were designed to hold their helium charge for two years and to have a MTBF of 500 h, while meeting typical military specifications for vibration, shock, acceleration, explosion, etc. Manufacturing cost was estimated at $625 each for a production of 7000 over 3.5 years.

Martin Marietta[51,52] has investigated manufacturing methods for the mechanical split cycle for the Army (Electronics R&D Command) with an objective to produce initially 10 units per week and later 400 per month. Inconsistent performance was noted for ambient temperatures below -40°F and was attributed to the degradation of seals. Several failures in compressor guides due to wear were corrected with a change in materials. The Martin Marietta design[53] produces 1 W of cooling at 80 K using 60 W of input power at 18.5 VAC. The compressor, of 2.4 in. diameter and 4.8 in. length, is separated by 24 in. from the displacer. However, the devices were unable to meet noise limits above 2000 Hz, torsional vibration requirements, and specifications for life and fluid leakage. Nevertheless, the shortcomings were regarded as being correctable.

Arthur D. Little, Inc.,[54] has developed a modified split mechanical Stirling cycle using rotating pistons with gas bearings. The modified cycle incorporates ports in conjunction with the rotating pistons, thereby leading to operation in essentially a reversed Brayton (or Ericsson) cycle. Staging is achieved through displacers of a stepped design. Balance is obtained through dual counterbalanced compressors and displacers. Gas springs on either side of the pistons permit operation at the resonant frequency. Rotation of the pistons is at 1200 rpm, while reciprocation is at 2400 rpm. Electronic controls regulate the stroke and phase relation, while temperature is fixed by electrical heating elements. The relatively large, 464-lb device requires 2670 W of input power at 100 VAC while producing 40 W of cooling at 60 K and 1.5 W of cooling at 12 K.

Ho, Howson, and Boland[55] discuss the nodal analysis of the class of split Stirling cycles including coupling of fluid-dynamic and thermal effects. They performed analytical solutions of the partial differential equations, thereby avoiding the stability problems of numerical methods.

Magnavox[44, 56] developed the Model MX 7045 split mechanical Stirling cycle for the Army according to government specifications. The device produces 0.25 W of cooling at 85 K using 25 W of DC input power with an objective of a 1000 h MTBF. Lindale and Lehrfeld[57] discuss a rhombic drive device developed for NASA producing 0.3 W of cooling at 90 K or 1.5 W of cooling at 140 to 170 K while using 30 W of input power. Bellows were attached to the base of the compressor piston in order to eliminate contamination from the crankcase; they were discarded from in-flight units after they were suspected of being the cause of degraded performance. However, laboratory testing of the bellows indicated that they should be useful to reduce the gradual increase in cold-side temperature from 0.4 K/day to 0.2 to 0.3 K/day.

The National Bureau of Standards (NBS) has conducted research on split mechanical Stirling cycles[58] for SQUID applications, which are very sensitive to magnetic fields. The objective is to avoid the use of mechanical components and good electrical conductors, perhaps supplemented by filtering of any signals that are produced. The cost should be not more than the SQUID device being cooled. Successively lower temperatures are achieved through staging: one stage for 50 K, three for 13 K, four for 8.5 K, and five for 7 K. Spun-glass epoxy cylinders and nylon displacers are used together with radiation shields. Little machining is required for the materials, but problems were encountered with contamination by air and with helium loss. The possibility of a continuously tapered displacer was investigated in order to minimize input power. Design details including bellows, ceramic cylinders, and clearance seals were also studied. Clarke, Taylor, and Amiri-Samkoey[59] were unable to reproduce the Zimmerman three- and four-stage split Stirling cycle performance with gap regeneration, pointing out difficulties with friction and gap contact. Sullivan et al.[60] state that efficiency is not critical for low power applications of less than 1 mW at 8 K. Instead, what is important is the ability to run at no load wherein all input power is used to intercept losses. Variational methods are discussed to optimize the plastic gas regenerator-displacer of the NBS design.

Magnavox[44] has also produced a split linear Stirling cycle, models MX 7040 and 7043, producing 0.25 W and 1 W of cooling, respectively, while using 45 W and 55 W of input power and weighing about 3.5 lb.

Ackermann, Bhate, and Byrne[61] discuss work by Mechanical Technology, Inc. (MTI) for the Army (Night Vision Laboratory) based on modifying a Honeywell split cycle designed for 0.25 W of cooling at 80 K to a linear drive. Improvements in reliability and performance were noted. Improved flexibility of the resultant design was also cited as a potential benefit for the regenerator.

Myrtle, Winter, and Gygax[62] describe an experimental device producing 6 mW of cooling at 9 K using a conical displacer of glass fiber and epoxy with radiation shields. Performance was limited by regenerative losses related to dead volume at the cold end and by nonuniform gas flow.

2.2.4 Vuilleumier Cycle

As discussed in Section 1 and indicated in Figure 4, the ideal VM cycle is a thermally powered refrigerator. Equivalently it is a heat-powered device driving a mechanical refrigeration device in one unit.

Hughes has developed a number of VM and modified VM devices. Doody[63] describes a 2-lb machine developed for the Army (Night Vision Laboratory) designed to produce 0.6 W of cooling at 77 K using 19 W of input power at 24 VDC after a cooldown time of 20 min. The life of the instrument was intended to be 100 to 1500 h depending on servicing. Noise was intended to be inaudible at 25 ft for the particular application. The VM cycle was selected because of its low pressure differential, leading to low stress and subsequent wear and contamination. The resultant device required considerably more input power than intended, namely about 80 W instead of 19 W, and was inaudible beyond 50 ft rather than 25 ft. Leo[29] notes that VM devices can be constructed to operate as predicted from thermal models with possible applications to an IR scanner system, a FLIR system, and a missile guidance system. The critical components were identified to be the regenerators, seals, bearings, and electrical (input) heating element. Berry[64] reports on a 4-lb modified VM cycle that incorporates a split cycle similar to the split Stirling cycle to produce 0.75 W of cooling at 77 K after 6 min of cooldown. A 2-W mechanical drive is used to power the compressor, but only to overcome losses and control speed. Heat input of 259 W is still used for the principal power source.

Five VM devices were produced by Hughes for the RF-4C aircraft AN/AAS-18 IR detector bay[65] in order to provide 2 W of cooling at 77 K with a goal of 1000 h MTBF.[66] However, the inverters on the drive motors failed prematurely. There was also an unexplained loss in cooling when the units were subjected to acceleration of 4 G. VM devices were also produced for the Air Force (AFFDL) for space applications.[67] A three-stage unit was designed to produce cooling of 12 W at 75 K, 10 W at 33 K, and 0.3 W at 11.5 K.

Features of the design included dry lubrication, C-seals on the displacer, and brazed-on electric heaters operating at 1250°F. Later,[30] the goal was to produce a 5-year MTBF with cooling of somewhat lower cooling levels (8.3, 1.9, and 0.3 W) capable of operating on a cyclic on-off basis. Tests indicated the desirability of using fluorogold seals on alumina rubbing surfaces.

Kinergetics[68] has developed improved fabrication techniques for a 0.6 W, 77 K cooler requiring 115 W of input power and intended to have a 7-min cooldown. Emphasis was on reducing the costs of the crankcase, cylinders, and insulation. A facility was to be constructed for the mass production of VM coolers; however, the prototype units were found to be deficient in performance, traceable to insufficient pressure ratio. Thus, attention was diverted to achieving thermal performance by reducing dead volume, by increasing hot-displacer stroke, and by reducing thermal mass. The increase in stroke was generally effective in increasing pressure ratio and cooling power, but only at the expense of input power and efficiency.[69] Reducing clearances and drive-belt slippages and using titanium for the cold cylinder led to improvements. It was determined that the hot cylinder could be spun from Inconel and that the fan shroud could be produced rotationally for $15 each.[70]

2.2.5 Turbomachinery

General Electric has produced a two-stage reversed Brayton cycle which provides 40 W at 60 K and 1.5 W at 12 K from 4 kW input power at 100 V.[71] The 100-lb unit has been designed for a 30,000 h MTBF. The main advantages of the turbo configuration are no sliding contacts, no valves, and no unsteady pressures. The device was confined to an envelope 27 in. in diameter and 55 in. long, exclusive of the 27 in. diameter and 28 in. long compressor.[72] A total of 20,000 h was accumulated on the gas bearings at 100,000 rpm. The major problem was in machining the tungsten carbide-coated thrust bearings; this was finally accomplished with extremely small diamond wheels.

Creare[73] has reviewed the chronological development of the turbocooler, originally proposed by Lord Rayleigh in 1898. Most recent designs have included gas bearings and modular construction in order to improve reliability and reduce construction costs.

2.2.6 Thermoelectric Devices

RCA[74] developed a cascaded device and found that a critical factor in performance was the technique of fabrication, which required over 100 steps with varying effects. It was pointed out that considerable trial and error would be required in order to prove a manufacturing approach.

Marlow Industries[75] has developed a device producing 25 mW of cooling at 175 to 195 K and used in a weapon-sight application. Battery power provides operation for 8 to 10 h. Four stages are used in the low coefficient of performance (COP) device. The critical aspects of design include the incorporation of effective heat sinks and controllers. In addition, the overall systems design should minimize the load on the cooler. Although the best performance was achieved with a switching proportional controller, a linear proportional controller was noted to be less costly and complex.

2.2.7 Passive Radiators

Philco-Ford[76] discusses the feasibility of passive radiators for an orbiter application. A proposed design used staged radiation shields, substantial insulation, and various novel structural elements in order to achieve a cold temperature of 81 K in the space environment. However, testing[77] led to achieving only 111 to 137 K due to excessive conductance through structural elements between the spacecraft, cooler, and radiator.

Lockheed[78] reports a design study of a cooler producing 5 W at 80 K for Titan III-B in a 226 lb, 64 ft^3 package. It is also expected to produce 0 W at 62.5 K or 10 W at 90 K with 36 percent of the effectiveness of a blackbody radiator.

2.3 COMPONENTS

2.3.1 Regenerator

As discussed previously, the regenerator is regarded as a critical component of the Solvay, Gifford-McMahon, Stirling, and Vuilleumier cryocoolers. The regenerator functions by storing and releasing heat of the working fluid as it flows between the hot and cold elements of the device. Efficiency and therefore power requirements are quite dependent on regenerator performance. Daney and Radebaugh[79] point out that one cannot realistically neglect the heat capacity of the flowing gas in the matrix-type regenerator, as is sometimes done. Gambardella and Orazi[80] have developed a comprehensive theory of operation for regenerators that should be useful for systems design and analysis. For example, in comparing various materials it was found that stainless steel has advantages over other alternatives.

2.3.2 Interface

Invariably, the cryocooler must be connected to another component. Most simply, the device to be cooled is mounted on a so-called cold plate that is in good thermal contact with the cold element. Alternatively, the cold element may interface with a reservoir of cryofluid that in turn provides the source of cooling to the load. This approach can be used to level fluctuations in the load as induced by either periodic behavior or transient response. Longsworth[81] gives guidelines for interfacing with liquid helium reservoirs at 4 K. The cryocooler itself should be self-contained and easily removable from the reservoir. Generally, this will entail separate vacuum systems used for thermal isolation. Several alternative designs are presented which meet the requirements.

2.3.3 Control

Temperature control is essential to proper operation of the cryocooler. A common source of failure is the control system itself rather than the basic cryocooler. Little, Inc.,[82] has developed an 8000-h hot-end temperature controller that operates at approximately 1200° to 1300°F using 28 VDC, although AC power was recommended in retrospect. The cost with sensor was estimated to be $350 to $470 for the requirements of the USAF. At the cold end, a commercial platinum resistance thermometer device (RTD) was incorporated. Generally, resistance heating is used to regulate cold-side temperature.

Spencer[83] discusses the concept of demand control wherein the device would run intermittently or at below rated capacity, thereby extending life and reducing power consumption and noise. The control would be fail-safe, reverting to normal cooling on failure. The results of tests on three 0.25 to 1 W devices were encouraging, with reductions in input power up to 50 percent and in noise of 5 to 10 dB. Life, vibration, and shock remain to be assessed.

2.3.4 Magnetic Effects

Cryocoolers are frequently used near magnetic fields, which should not be perturbed by the cryocooler operation. One approach previously discussed is the use of nonmagnetic materials, as accomplished in the approach of NBS. Alternatively, Steyert and Longsworth[84] discuss correcting the magnetic field for perturbations of the device or simply isolating it with distance from the critical area. The effect of magnetic fields on the order of 500 G appears small in terms of the influence on the cryocooler. A split design permits isolation except for the cold element itself.

3. CURRENT STATUS

3.1 EVALUATION

Infrared detection devices generally require on the order of 1 W of cooling at 10 to 100 K, typically 80 K (see Figure 6). A number of devices are currently commercially available for providing the necessary cooling. Reciprocating devices, such as those operating on the Stirling, Vuelleumier, Solvay, and Ericsson cycles and the like, appear generally suitable for closed-cycle operation. Closed-cycle devices are advantageous in terms of the logistics of storage and maintenance and in terms of being compact and lightweight--important factors in missile and high-performance aircraft applications as well as in ground-based combat equipment.[85]

Generally, devices incorporating Joule-Thomson (J-T) expansion valves suffer from potential clogging of the active element, the valve, due to the contaminants always present. Passive radiators may have suitable applications in space where a low-temperature cooling reservoir (space itself) is available, but they are clearly not suitable for the applications of interest here except perhaps in relation to minimizing the cooling load by the incorporation of radiation shielding. Thermoelectric (Peltier) devices are conceptually attractive, but material limitations have prevented their development for the cooling range of interest. Only if extraordinary design measures are taken would thermoelectric devices be suitable, and even then, they appear to be particularly sensitive to manufacturing techniques in terms of achieving predicted performance. Turbo cryocoolers are potentially attractive because of their lack of pressure and other force fluctuations, but they are perhaps more suitable for larger cooling loads.

As pointed out by Chellis,[21] each cryocooler application has special needs that can best be met with a custom design that is specified in cooperation with the cryocooler and electro-optic designers early in the system program. At the same time, the military has a great need for large numbers of similar devices, which suggests standardization. Many system designers, including the present reviewers beleive that both of these needs can generally

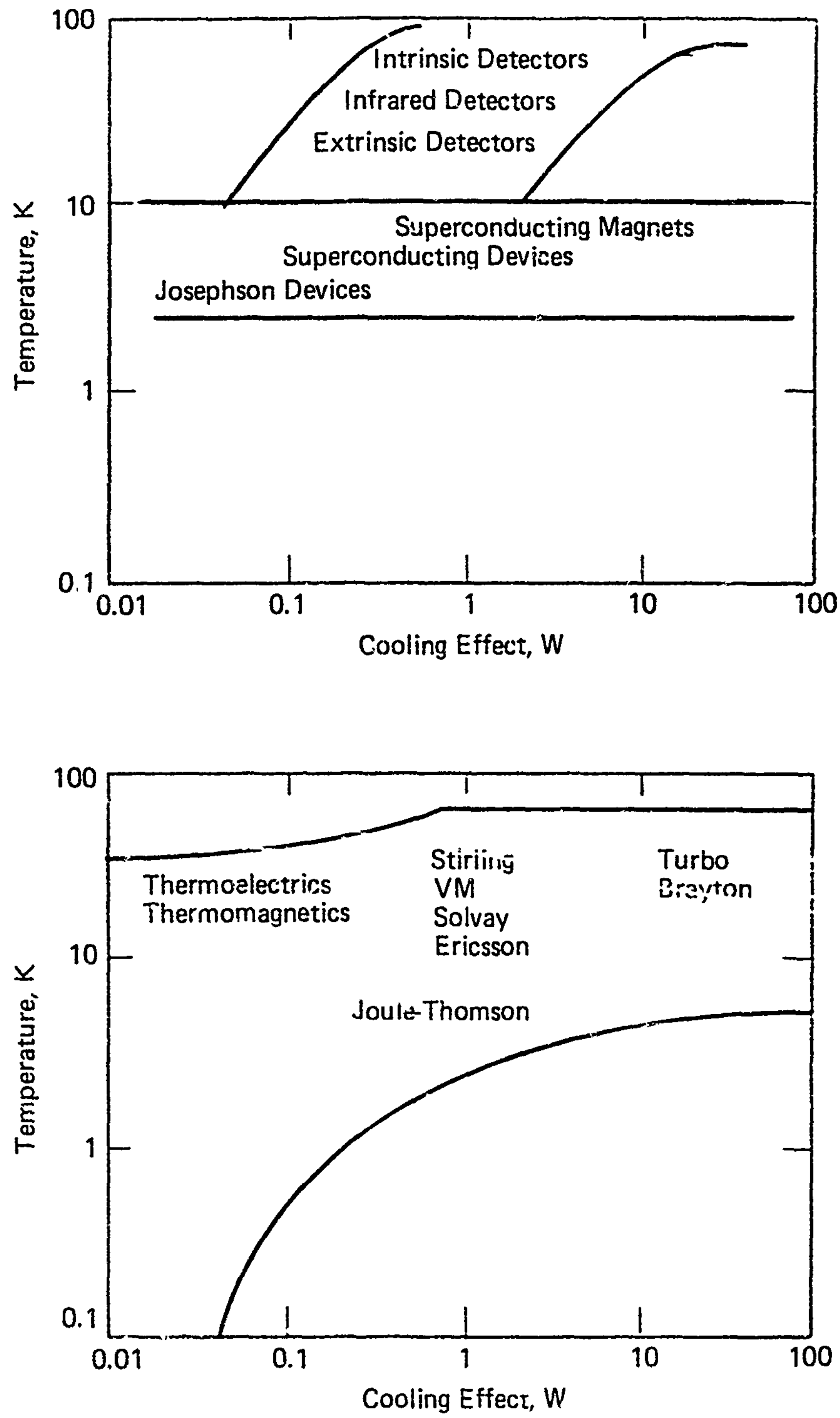

Figure 6. Regime of IR detection requirements and available cryocoolers (based on Johnson[24]).

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be met by a modular approach. In the case of a particular cooling load, one would add modules in parallel in order to achieve the desired capacity. In the case of a particular cold-sink temperature, one would add modules in series, thereby staging the cooling cycle. Although still emerging, one present technology appears well suited to the modular approach. The technology is that associated with microminiaturization.[35,36] Microminiaturization involves etching the cryocooler conduits, heat exchangers, etc., into a substrate with specially designed companion diaphragm compressors used for power. At present, only Joule-Thomson cycles appear to be available. While these are susceptible to clogging, the developers allude to a design concept incorporating redundant circuit paths, thereby achieving the desired reliability. In addition to the benefits that a modular approach affords in design and fabrication, the concept of microminiaturization offers the opportunity of more fully integrating the cryocooler into the electronics to be cooled. Currently, this approach is being exploited in devices designed for ultra-fast cooldown, on the order of seconds.

Early cryocoolers had to have long life and high reliability, requirements which led to conservative designs incorporating oil-lubricated compressors of large size and weight. The Gifford-McMahon cryocooler served well in such applications as ground-based satellite stations and the FLIR detector of the B-52 bomber. However, high-performance aircraft applications require higher operating speeds and pressures in order to reduce size, weight, and input power. Often dry lubrication is employed, and shorter life and maintenance intervals are accepted as being necessary to achieve constraints. The Stirling cycle and its variations, such as the Ericsson cycle with a rotating piston and ported cylinder, seem especially useful. The Vuilleumier cycle, which is principally thermally driven, offers the potential of reducing operating and maintenance costs over the entire life cycle, because of advantages in reduced wear due to lower pressure operation. In space, it appears necessary to employ magnetic bearings and direct linear drive in order to achieve the desired long life, which today is typically targeted as five years.[21]

A number of specific devices currently available merit special mention as being in the forefront of the technology demanded in space. These include the Arthur D. Little rotary reciprocating refrigerator, the Hughes Aircraft Co.

Vuilleumier device, the Philips Laboratories (U.S.A.) Stirling cycle, and the AiResearch/Garrett turbo Brayton refrigerator.[24] The Little refrigerator has a the rotating piston with a ported cylinder and operates on the Ericsson cycle. However, the bearing and porting requirements imposed on the low-temperature displacer result in a need for close tolerances and clearances, which have been difficult to achieve. The Hughes VM device uses sliding composite seals and riders and a rotary-to-reciprocating mechanical drive to shuttle the displacers with the proper phase relation. The present mechanism uses dry-lubricated ball bearings and Bendix flexure bearings. The design is limited in wear and fatigue life, and the conversion from thermal to mechanical energy results in low efficiency. The Philips line of Stirling cycles with magnetic bearings and linear drive virtually eliminates wear, but at the expense of simplicity. The AiResearch turbo cryocooler uses foil-type gas bearings to minimize wear, but also at the expense of simplicity; this seems justified only if very long life is needed, as in spacecraft applications.

The above considerations suggest that for missile application, the ordinary miniature Stirling cycle, or its related Solvay or Ericsson cycles, may be most suitable. In this application, maintenance incurred by normal operation is not an issue. Instead, one needs high performance in terms of compactness, lightness, and low power consumption with reliability for one-shot operation. Of course, ground logistics may require testing under active operation, but this would probably require relatively few hours compared with aircraft or spacecraft applications. The ideal device would be sealed and ready on demand, either for testing or for deployment. Thus, it appears that one does not require the sophistication of magnetic suspension or linear drive. However, if a low degree of microphonics is required, the split Stirling cycle (or related cycle) may be advantageous so that the active cooling element can be separated from the rest of the device, thereby minimizing interference. Nonmagnetic materials may also be used in either an integrated or split system. With staging, lower temperatures can be achieved depending on the requirements of the sensor to be cooled.

3.2 COMMERCIAL INFRARED CRYOCOOLERS

A number of U.S. and foreign manufacturers produce closed-cycle cryocoolers suitable for IR detectors (see Table 3). Generally, these are in the cooling range of 0.25 to 2 W at about 80 K.[20] The devices currently available are predominantly Stirling cycles, including both split and integrated versions, although there are also a number of Joule-Thomson devices and a few Vuilleumier and Gifford-McMahon units. Some of the cryocoolers qualify for characterization as so-called common-module devices meeting military size, weight, and performance requirements.

TABLE 3. MANUFACTURERS OF COMMERCIAL AND PRODUCTION TYPE CLOSED-CYCLE CRYOCOOLERS SUITABLE FOR IR DETECTORS[20]

Manufacturer	Type[a]
AiResearch	Joule-Thomson
Cryosystems, Inc.	--
CTI--Cryogenics	Stirling Vuilleumier Gifford-McMahon
Hughes Aircraft	Stirling Vuilleumier[b]
Magnavox	Stirling
MMR, Inc.	Joule-Thomson
Texas Instruments	--
H. R. Textron	Stirling
M. V. Philips (Holland)	Stirling
L'Air Liquide (France)	Stirling
A.B.G. Semca (France)	Stirling
Galileo (Italy)	Sterling
Ricor (Japan)	Stirling Vuilleumier

[a]Typically providing 0.25 to 2 W at 80 K.

[b]Staged to 0.15 W at 12 K.

Generally, the mass of the cryocoolers is in the range of 2 to 5 kg/W, and the volume is contained in a parallelopiped of about 20 L/W. Coefficients of performance (COP) are typically 0.01 to 0.02 corresponding to 100 to 50 W (input)/W (output). Thousands of these devices have been produced in the U.S. and abroad. The reader can refer to the cited reference[20] for more details about individual devices and manufacturers.

It appears that the conclusion of the marketplace is essentially the same as that of this report: that the Stirling cycle is most suitable for the IR detector application.

3.3 RESEARCH AND DEVELOPMENT

Table 4 lists the organizations currently developing advanced cryocoolers. As can be seen, most of the activity centers about the Stirling cycle, just as in the case of commercial devices.

TABLE 4. CURRENT DEVELOPMENT ACTIVITY IN CLOSED-CYCLE CRYOCOOLERS SUITABLE FOR IR DETECTORS[20,27]

Organization	Activity
Energy Research and Generation	Split Stirling Cycle
General Pneumatics	Claude Cycle
Kryovac Scientific	Split Stirling Cycle
MMR, Inc.	J-T on a Chip
U.S. Army Night Vision Lab	3-Stage Stirl ng Cycle
Hymatic Co. (U.K.)	J-T
L'Air Liquide (France)	Split Stirling Cycle
Oxford University (U.K.)	Split Stirling (Linear)
Philips (Holland)	Split Stirling (Linear)

Many organizations are doing sponsored and proprietary research in cryocooler technology. Table 5 gives a representative list of these organizations, together with an indication of their principal activities. Although this list includes work in areas that may be more appropriate for applications other than IR detection, research and development at the basic level has the potential to benefit a wide range of applications, perhaps beyond that

TABLE 5. BASIC RESEARCH AND DEVELOPMENT ON CRYOCOOLER TECHNOLOGY[20,22,27] (page 1 of 2)

Organization	Activity
Air Products	Regenerators Compact Heat Exchangers Compressors (noncontaminating) Materials
Carlisle Cryotronics	Compressors (noncontaminating) Seals
Creare, Inc.	Rotary Expanders Compressors (noncontaminating)
Cryogenic Technology, Inc.	Seals Cycle Analysis MACOR Materials
CVI	J-T Augmentation of Stirling/G-M
Energy Research and Generation	Compressors
General Pneumatics	Claude cycle
Hughes Aircraft	Cycle Analysis
Jet Propulsion Laboratory	Absorption Cycle Compressors (noncontaminating)
Lakeshore Cryotronics	Expanders Pneumatic Drive Mechanism
Magnavox	Expanders Seals
MMR Technologies	Etched Heat Exchangers J-T on a Chip Diaghragm Compressor
MIT	Saturated Vapor Recompression
Mechanical Technology, Inc.	Compressors (noncontaminating)
Metal Bellows Corp.	Compressors
Naval Research Laboratory	Compressors (noncontaminating)
NBS	Regenerators Nylon and Ceramic Materials Compressors
Philips (U.S.A)	Regenerators Materials Triple-Expansion Cycles Linear Drive
Rockwell International	Gas-Absorption Compressors
Santa Barbara Research	Metallic Heat Exchangers

TABLE 5. BASIC RESEARCH AND DEVELOPMENT ON CRYOCOOLER TECHNOLOGY[20,22,27] (page 2 of 2)

Organization	Activity
SHE Corp.	Nylon and Fiberglass Materials Helium Gas Regenerators
Aisin Seiki Co. (Japan)	J-T Augmentation
Daikin Industries, Inc. (Japan)	Expanders Compressors
Hitachi (Japan)	Regenerators Claude Cycle
Hymatic Engineering (U.K.)	Compressors
JNR (Japan)	Cycles
L'Air Liquide (France)	Expanders Compressors
Mitsubishi Electric (Japan)	G-M + J-T Cycle
Nihon University (Japan)	Regenerative Cycles
Oxford University (U.K.)	Seals Expanders
Philips (Holland)	J-T Augmentation
Sumitomo (Japan)	Cycles Heat Exchangers Compressors Expanders
Tohoku University (Japan)	Stirling Cycle
Tokoyo Institute of Technology (Japan)	Magnetic Cycle
Toshiba (Japan)	Cycles Heat Exchangers Compressors Expanders
Y. Ishizaki (Japan)	Stirling Cycle

intended by the funding authority, whether the organization itself or an external sponsor.

Essentially, research and development can be classified in terms of cycle analysis including loss mechanisms, regenerator development, heat exchanger design, expander design and development, compressor development, seal material, and contamination elimination.[20] Perhaps the area of most common interest is that dealing with the compressor. Concern with the compressor probably reflects its nature as the greatest source of wear and contamination and as the greatest contributor to size and weight. Even so, as discussed in Section 2, other components such as the regenerator may limit performance in a specific device.

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1. *Develop a machine-readable bibliographic data base-- currently containing over 30,000 entries;*

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3. *Analyze, appraise and summarize information and data on selected subjects;*

4. *Disseminate information through the GACIAC Bulletin, bibliographies, state-of-the-art summaries, technology assessments, handbooks, special reports, and conferences;*

5. *Respond to technical inquiries related to tactical weapon guidance and control; and*

6. *Provide technical and administrative support to the Joint Service Guidance and Control Committee (JSGCC).*

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